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Quantitative Measurement of Rainfall by Radar

by

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A paper presented on May 25,1954, at the Annual Conference, Seattle, Wash., by A. M. Buswell, Chief; G. E. Stout, Head, Meteorologic Subdiv.; and J. C. Neill, Meteorologist; all of State Water Survey, Urbana, Ill. (Investigation jointly sponsored by US Signal Corps Eng. Labs. and State Water Survey under Contract No. DA-36-039 SC 42446.)

THE standard rain gage does not give a good estimate of areal rainfall, but merely measures the rainfall in the immediate vicinity of the collector. During World War II it was observed by the military that certain radar frequencies were detectors of precipitation. At the close of the war preliminary work was done by the armed forces at the Massachusetts Institute of Technology on the detectability of meteorological parameters by radar. In 1948 the Illinois Water Survey became interested in the utility of radar for quantitative measurement of summertime precipitation in the state. Special networks of rain gages were established to define their accuracy at various gage densities and to check it against radar measurements of rainfall. This paper summarizes some of the results obtained from dense rain gage networks and from radar observation of rainstorms during the past 2 years.

Storm Rainfall Variability

Extreme variability of rainfall over small areas, 100 sq miles or less, has been recorded by gages spaced approximately 1½-2 miles apart *(1)*. The variability of point storm rainfall amounts and the areal rainfall distribution patterns for several summer rainstorms are shown in Fig. 1-3. These isohyetal maps were prepared from 50 recording gages within a 96-sq mile area on the Goose Creek watershed. The network is centered approximately 20 miles west of Champaign-Urbana, Ill.

In Fig. 1, the rainfall patterns for Jul. 13 and 17, 1952, represent storms of short duration and very low average rainfall (less than 0.05 in.) over the network. The differences between in-

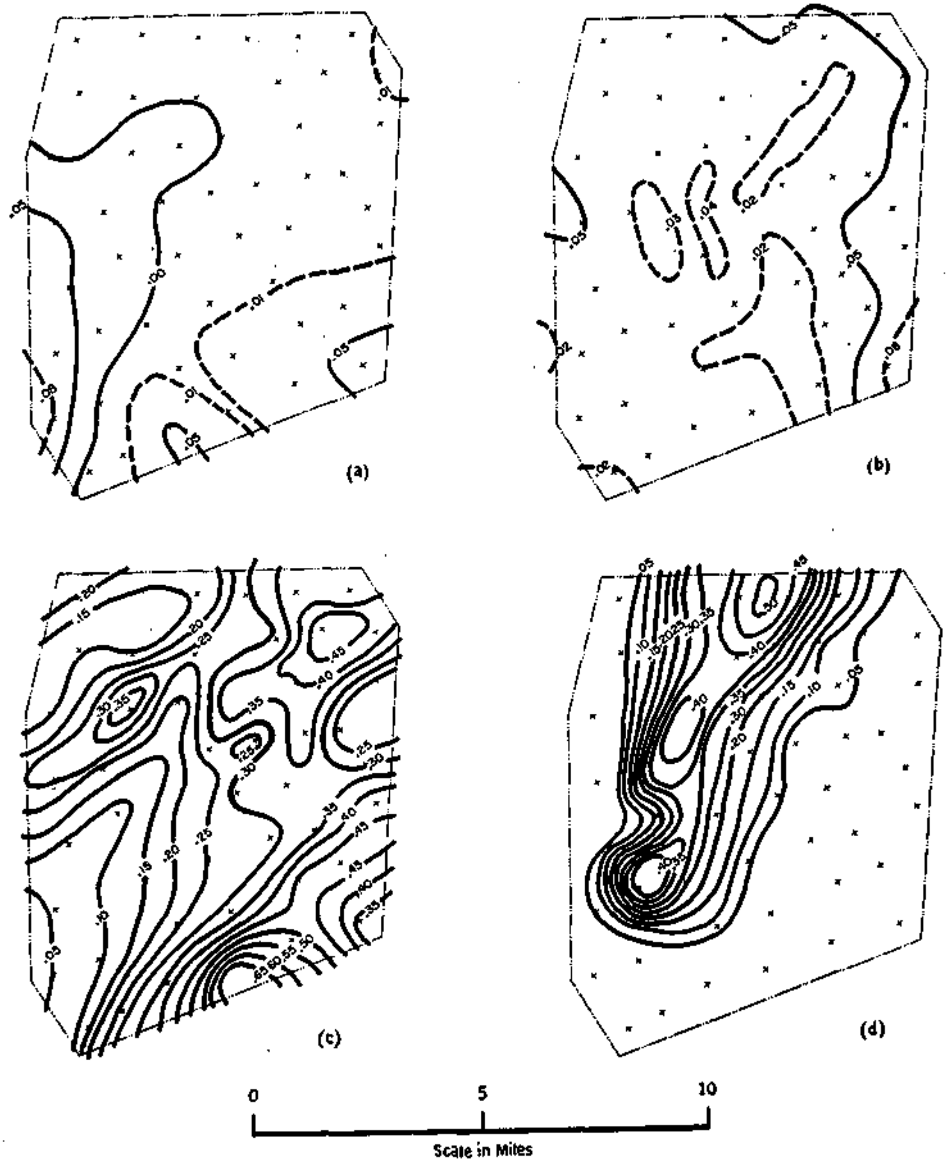


Fig. 1. Light-Rainfall Variability

The average amount and duration of rainfall on various dates (1952) were, respectively: (a) *Jul. 13—0.03 in., 45 min; (b) Jul. 17—0.04 in., 20 min;* (c) *Jul. 16—0.26 in., 70 min; (d) Aug. 3—0.16 in., 10 min.*

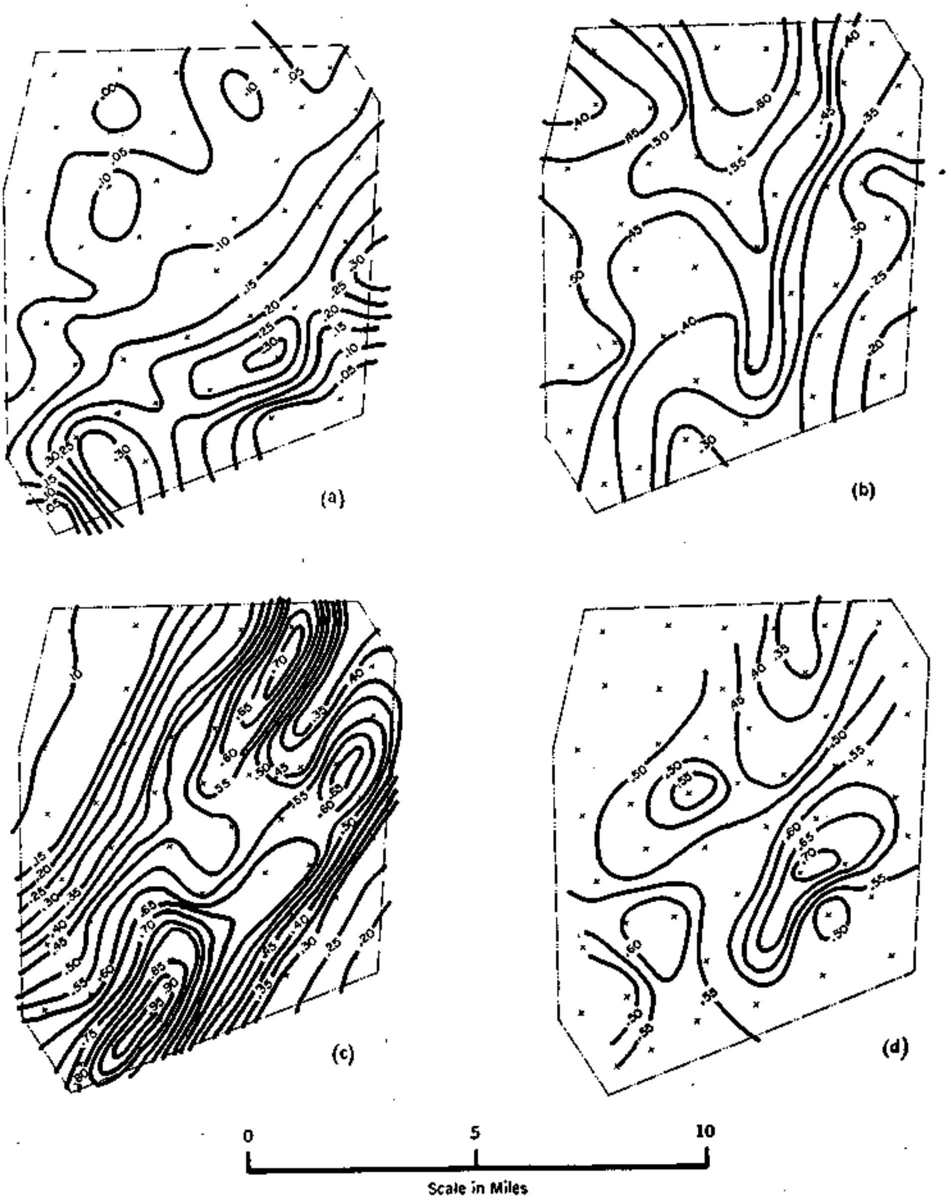


Fig. 2. Medium-Rainfall Variability

The average amount and duration of rainfall on various dates (1952) were, respectively: (a) *Jul. 14—0.16 in., 10 min; (b) Jul. 7-8—0.40 in., 120 min;* (c) *Aug. 3—0.48 in., 105 min; (d) Jun. 20—0.52 in., 105 min.*

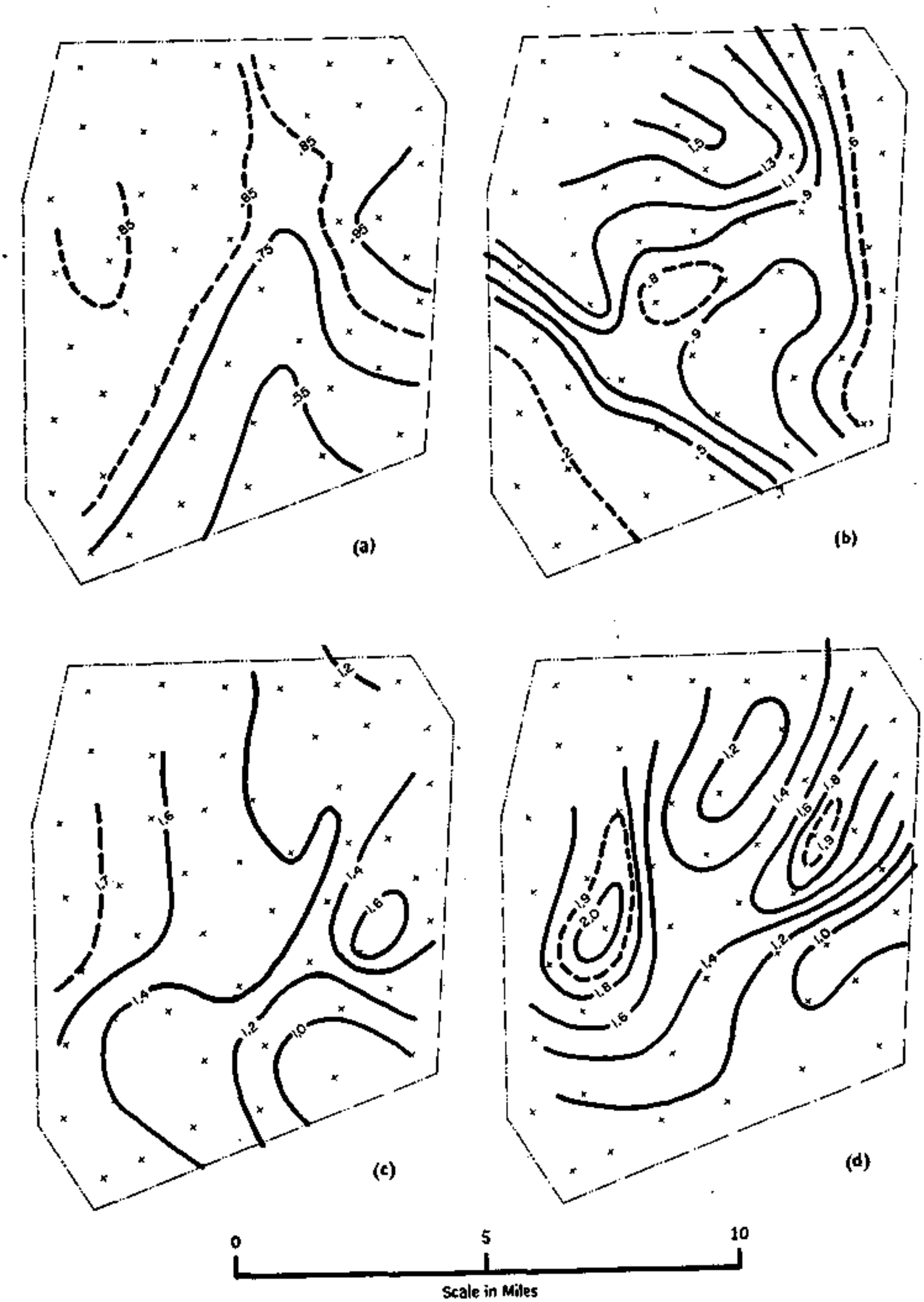


Fig. 3. Heavy-Rainfall Variability

The average amount and duration of rainfall on various dates {1952) were, respectively: (a) *Jun. 21—0.79 in., 90 min; (b) Jul. 2—0.84 in., 180 min;* (c) *Jun. 13—1.41 in., 120 min;* (d) *Jun. 22-23—1.42 in., 180 min.*

dividual gage readings likewise are small, amounting to 0.08 in. or less, The storms of Jul. 16 and Aug. 3 show rainfall patterns that are considerably more variable than those of the other two storms in Fig. 1. One has a mean rainfall of 0.16 in., and the second 0.26 in. The range of individual values on Jul. 16 was 0.05-0.65 in. in a distance of 3½ miles. The storm of Aug. 3 exhibits very high rainfall gradients—up to 0.25 in. per mile. Precipitation was very intense over part of the network and diminished rapidly from the core to the outside edge of the rain area, leaving a considerable portion of the network without rainfall.

It is evident that several gages are necessary to obtain an accurate measurement of mean rainfall over the affected area for a storm like that of Aug. 3. One gage located near the center of the network would have recorded a rainfall amount of about 0.15 in., which, although a good representation of the network mean in this instance, tells little about the rainfall that occurred over the remainder of the network. Moreover, it is possible for rainstorms of this size to pass between gages spaced 8 miles apart.

The isohyetals shown in Fig. 2 represent rainfall of longer duration and greater average depth than that in Fig. 1. These four isohyetal maps represent a variety of rainfall distribution patterns and gradients. A second rainstorm on Aug. 3 produced three distinct cores of high rainfall within the 96-sq mile network, and there were several zones in which the rainfall gradient was of the order of 0.35 in. per mile. The range in point rainfall measurements was 0.10-0.95 in., a considerable variation for an area of this size. The rainfall cores and gradients in the other three diagrams in Fig. 2 are much less intense. No distinct rainfall centers were found in the network area for the Jul. 7-8 storm.

Figure 3 shows typical examples of distribution patterns for a mean rainfall of 0.75 in. or more occurring over a period of 1½ hr or longer.

The isohyetal patterns have illustrated the fact that rainfall often varies widely. Several distinct rainfall centers for single storms are common in an . area of 100 sq miles, and the amount of rainfall frequently varies 0.25 in. in a distance of 1 mile. Storms of long duration tend to produce greater relative uniformity in rainfall patterns than do storms of short duration and high rainfall rate.

Seasonal Rainfall Variability

During a thunderstorm season numerous rainstorms deposit rainfall on a watershed. The accumulation from several storms tends to produce areal rainfall distributions with smaller relative differences among individual point rainfall amounts than those from single thunderstorms. The variance in seasonal point rainfall amounts, however, is large. The three isohyetal maps in Fig. 4 illustrate seasonal thunderstorm rainfall variability over the Goose Creek network from Jun. 1 to Oct. 31 for the years 1951-53. The greatest difference between point rainfall amounts was approximately 2 in. in 1½ miles for the 1951 season, 2 in. in 2 miles for 1952, and 2 in. in 1 mile for 1953.

Sampling Variance Study

A sampling variance study was made on point rainfall values for the purpose of obtaining an estimate of the standard error to be expected in calculating areal mean storm rainfall from various gage densities (2). In this study, the different sample sizes or

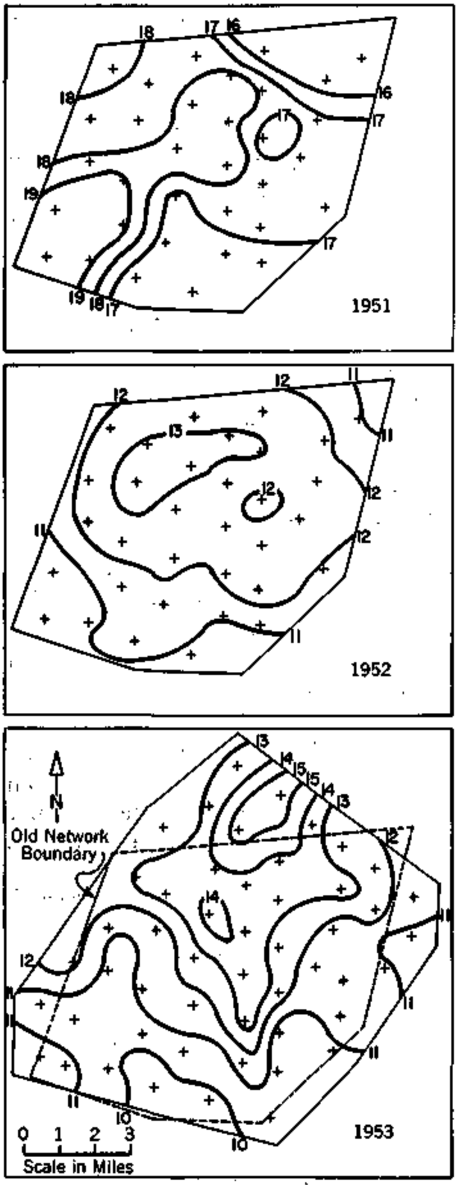


Fig. 4. Cumulative Rainfall

The average rainfall (in inches) for the period Jun. 1-Oct. 31 in the years 1951, 1952, and 1953 was, respectively: 17.32, 12.12, and 12.07.

gage densities were obtained by dividing the network area into sections and selecting gages located near the center of the sections. Figure 5 shows the relation of the sampling standard error to the storm size (as indicated by the gage network mean rainfall) and to the sample size (the number of gage observations included). It is evident from the graph that the expected sampling standard error increases as the storm size increases and as the number of gages in the sample decreases. For example, the error to be expected in the measurement of a ½-in. network mean rainfall with eight gages is 0.030 in., while, for a 1-in. mean rainfall, the error is 0.045 in. The errors to be expected for the same storm sizes when one gage is used are 0.102 in. and 0.151 in., respectively.

The sampling standard errors shown in Fig. 5 are essentially average errors in the measurement of areal mean rainfall for different storm sizes when various rain gage densities are used. It is important to note that average values always cover up the extremes. The diagram in Fig. 6 shows 95 per cent confidence bands for mean rainfall based on estimated mean rainfall samples from different gage densities. These bands include approximately 95 per cent of the individual deviations of sample means from the 50-gage network mean. Although the average expected errors shown in Fig. 5 may lead one to feel that the sampling errors are not very serious, Fig. 6 shows that a band of considerable width is necessary to encompass the greater part of the individual errors averaged in the expected standard error. For example, when a 1-in. mean rainfall is obtained with a density of one gage per 96 sq miles, the true network mean rainfall may be between 0.70 in. and 1.30 in. This is an error range of 0.60 in. or ±30 per cent. As the number of gages used in obtaining an estimate of the mean rainfall is increased from one to 24, the 95 per cent confidence region narrows to 0.10 in. for a 1-in. mean rainfall.

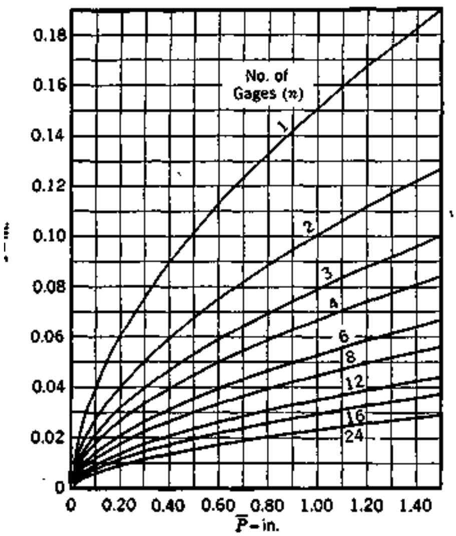


Fig. 5. Sampling Standard Error

Key: s, *standard error of estimates for samples of size* n *(number of gages) ;* P, *population mean rainfall based on 50 gages. Data for 45 storms occurring over Goose Creek netzvork in 1952 and 1953.*

Radar Measurement Program

Evidence has been presented that rainfall is variable and that a large number of gages arc needed to obtain a good estimate of areal mean rainfall, especially when shower type precipitation is involved. This type produces most of the annual rainfall in Illinois.

The present network density in Illinois is approximately one gage per 225 sq miles, which does not provide the accuracy desired by engineers and hydrologists. The expense of increasing the density to that needed and of collecting and compiling the hydrological data would be prohibitive. Accordingly, the State Water Survey initiated an investigation in 1948 to determine the ability of radar to provide quantitative rainfall measurements. The Pfister Hybrid Corn Co., El Paso, Ill., cooperated in the first study to detect, track, and measure the areal extent of shower type rainfall. A war surplus 3-cm radar set was installed. A network of 35 stick and twelve recording rain gages was installed over an area of approximately 280 sq miles in the vicinity of El Paso, in order to obtain simultaneous surface rainfall measurements for correlation with the radar observations and for investigating thunderstorm rainfall variability *(3).*

Operations during the thunderstorm seasons of 1948-49 proved that radar could successfully detect, track, and indicate the areal extent of precipitation in showers and thunderstorms. An evaluation of the quantitative aspect of rainfall measurement with radar was begun in. 1950. Concurrently with the State Water Survey's work, the University of Florida published the results of some analyses of radar rainfall data previously collected *(4).* Operations during the summer of 1950 were encouraging (5), although limited by the modification of the radar equipment for quantitative observations.

Early in 1951 the radar equipment was moved to the University of Illinois airport, near Champaign-Urbana, to facilitate operations. A concentrated network of 34 recording gages, with

12.648-in. diameter collectors and 6-hr charts, was installed over an area of 50 square miles on the Goose Creek watershed. During the 1952 thunderstorm season the program for quantitative measurement of rainfall with radar equipment was expanded considerably with support from the US Army Signal Corps (6). The number of gages on the Goose Creek watershed'was increased to 50 in 96 sq miles.

Figure 7 shows the main components of the APS-15, 3-cm wavelength radar set used in the program. The center rack consists of a receiver-indicator, a camera on a remote scope, a plotting board, and various controls, The unit on the right, known as an area integrator, will be discussed briefly later. The radar antenna is located on a 47-ft tower to obtain an unobstructed scanning view in the direction of the Goose Creek rain gage network.

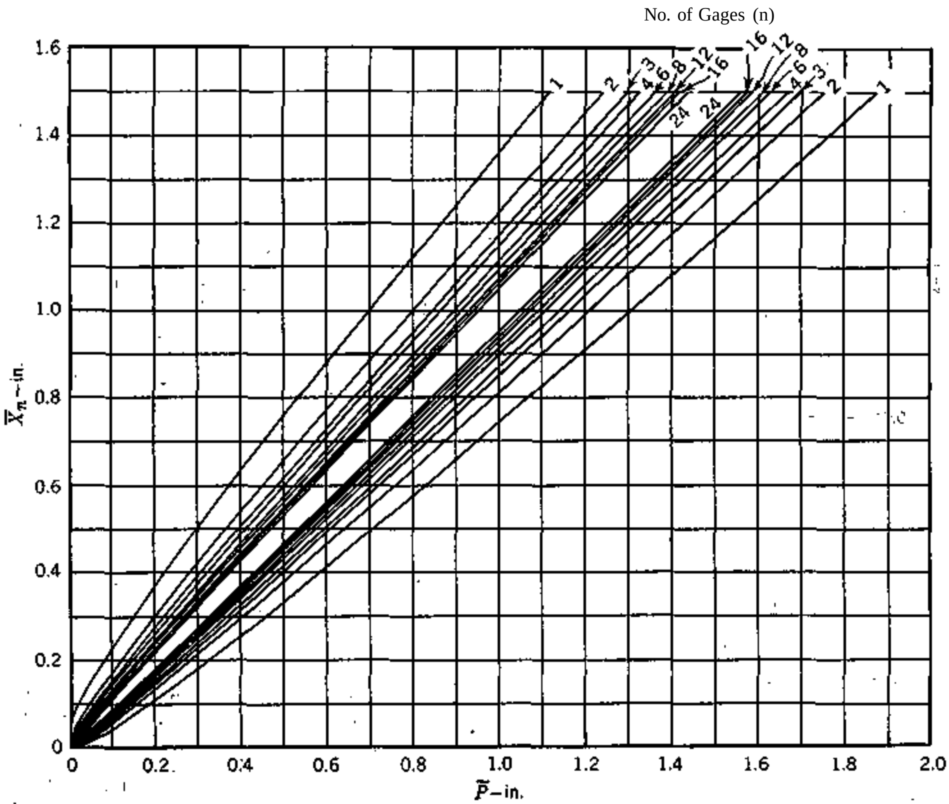


Fig. 6. Ninety-five Per Cent Confidence Limits

Key:. $\bar{X}_n$, *estimated mean rainfall for samples of size* n, *(number of gages)* ; $\bar{P}$, *population mean rainfall based on 50 gages. Goose Creek data, 1952-53.*

Principle of Radar

Radar is a high-frequency radio device emitting a short, intense pulse of energy that is focused into a narrow beam of invisible energy by a rotating antenna, much like a searchlight. This pulse of energy travels at the speed of light. If the beam strikes an object, such as an airplane or a group of raindrops in a cloud, a small portion of the energy is reflected back as an "echo" to the point of transmission. The return signal is amplified and presented on a cathode ray tube. The range and bearing of the object are readily determined.

Research in this field by previous investigators *(7, S)* indicated that radar echoes from rain clouds are the result of the back-scattering of radio energy by raindrops falling through the atmosphere. It appears from the theory that the energy (or power) received from raindrops may be expressed by the equation:

$$\frac{P_r R^2}{P_t} = KNd^6 \ldots\ldots\ldots (1)$$

in which P_r is the power received, P_t is the power transmitted, 7? is the distance from the radar set to the reflecting raindrops, N is the number of raindrops per unit volume, d is the diameter of the raindrops, and K includes a constant for the refractive index of water and a number of constants that are parameters of the radar set.

Radar does not measure rainfall intensity directly, but measures the re-

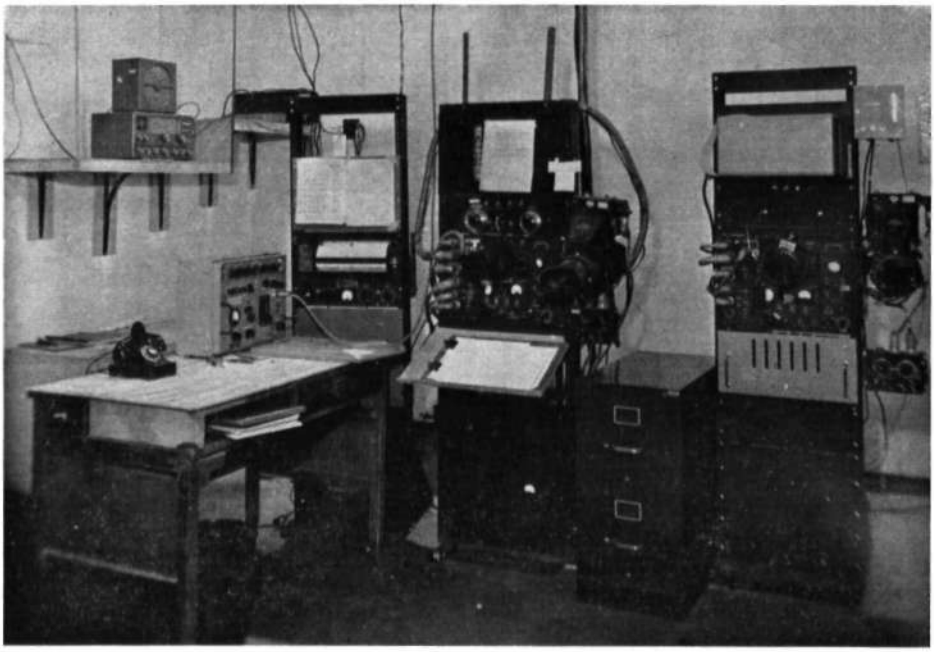
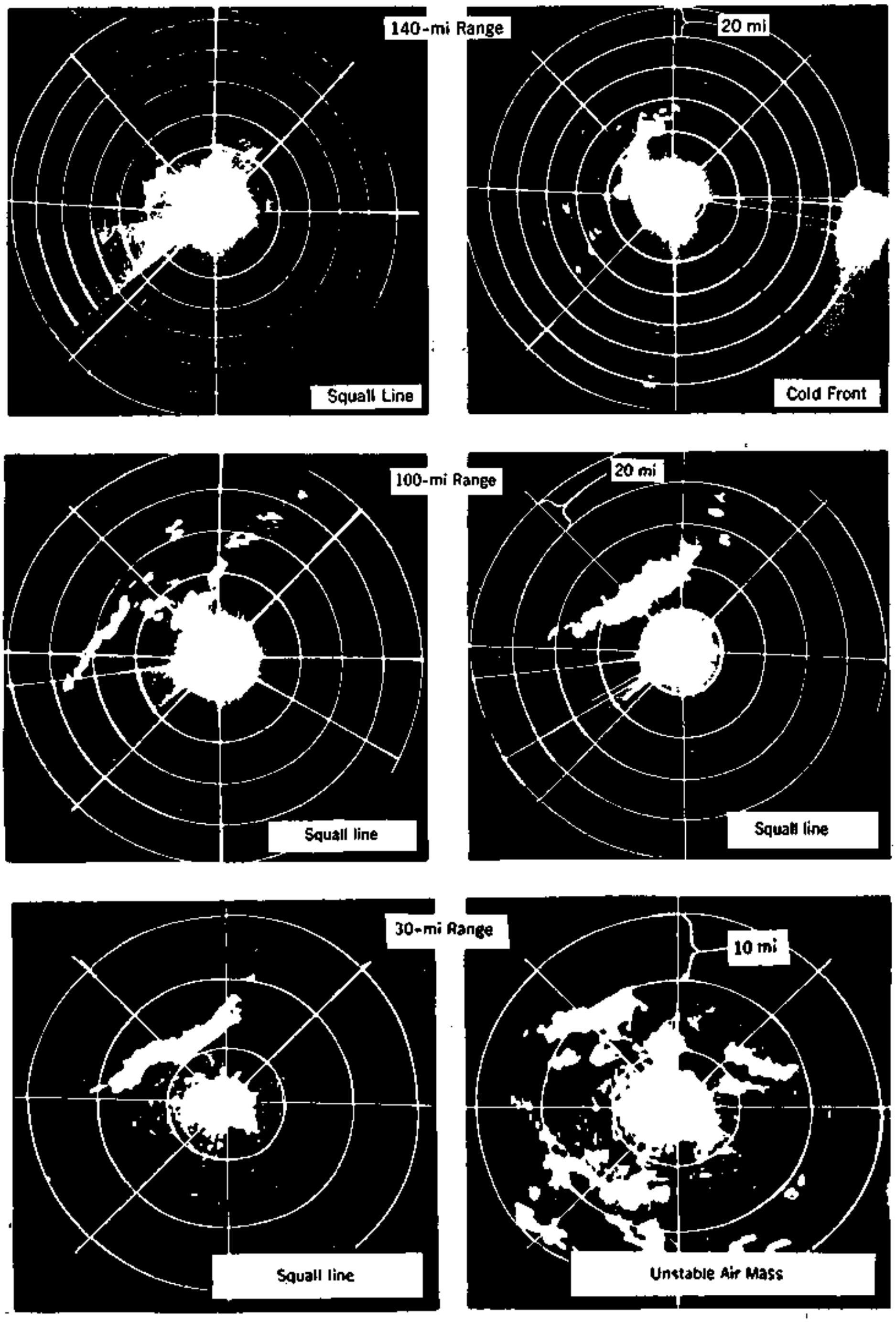


Fig. 7. Radar Room

The center rack consists of a receiver-indicator, a camera, a plotting board, and various controls. At right is an "area integrator."



Tig. 8. Bain Echo Patterns

flectivity from Nd^B. Several expressions for the rainfall rate in terms of Nd^a have been obtained from raindrop size data. One of these expressions is:

$$Nd^6 = K_2 I^{1.53} \ldots\ldots (2)$$

in which I is the rainfall intensity and K_2 is a constant of proportionality. When Eq 2 is combined with Eq 1, the resulting equation, written in logarithmic form, for the APS-15 model, is:

$$\log \frac{P_r R^2}{P_t} = 1.53 \log I - 10.932 \ldots (3)$$

in which I is the rainfall rate in inches per hour.

Radar Patterns

The low-powered APS-15 radar set generally detects precipitation up to 140 miles. Numerous types of rainfall patterns are observed. Figure 8 gives some examples of the appearance of the plan position indicator (or face of the cathode ray tube) in different weather situations—cold front, squall line, and unstable air mass. Rainfall occurring in unstable air mass situations usually shows scattered echoes about the radar station, while a line of echoes is generally characteristic of cold-front and squall line rainfall. Shorter range settings (Fig. 8, bottom) provide an enlarged and more detailed record of a smaller precipitation area than longer ones and facilitate the analysis of data over the Goose Creek area.

Radar Rainfall Intensity Technique

Rainfall intensity data can be obtained from the radar echo pictures. A. receiver sensitivity control system developed for use on the State Water Survey radar set automatically changes the radar receiver sensitivity in a stepwise fashion, using fixed settings'. Each time the receiver sensitivity is reduced, a greater rainfall intensity is required before an echo will appear on the plan position indicator. Thus, the system indicates areas of different rainfall intensities. An automatic film recording system was synchronized with the receiver sensitivity control so that photographs of rain echo areas could be taken.*

The results obtained by using the automatic sensitivity control and 35-mm film recording technique are illustrated in Fig. 9. Figure 9a shows the entire rain echo obtained with maximum receiver sensitivity during one 360-deg rotation of the radar antenna. As the next rotation began, the receiver sensitivity was reduced to the second highest fixed setting, causing the areas of lightest rainfall to be eliminated (Fig. 9b). This process was repeated through a series of six steps, with the photographs showing smaller and smaller rainfall areas. The film record consists of repeated series of pictures taken at 1-min intervals during a storm.

As the radar tracks the path of a storm, a detailed record of movement and rainfall intensity is compiled. The date and time of each rainfall intensity area sample is also recorded on film. The photographs in Fig. 9 were taken with the range set at 30 miles.

Radar and Gage Comparison

The next question of interest is how well the low-power 3-cm radar record compares with the rain gage record on the ground. Superimposing the images of a series of photographs like those in Fig 9 on a single base map

* The illustrations in Fig. 8 and 9 are photographs that have been reproduced here by a linecut (rather than the more usual halftone) process for improved clarity.

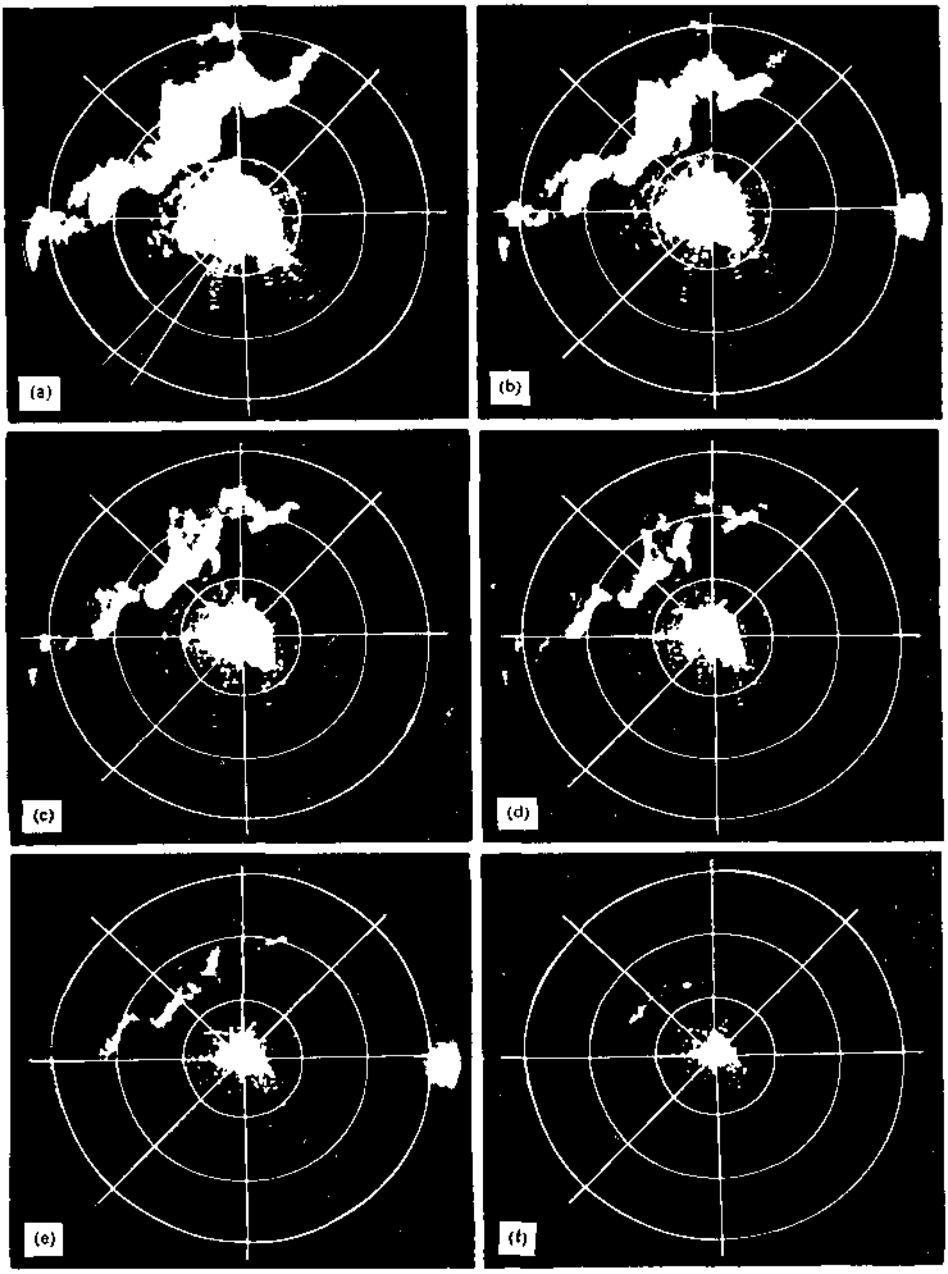


Fig. 9. Effect of Sensitivity Control

Photographs (a) *through* (/) *show the results of progressively decreasing receiver sensitivity. The photographs were taken at 1-min intervals during a storm on Jun. 5, 1953.*

permits the preparation of a radar rain intensity contour map for the Goose Creek area. Such maps can then be compared, as in Fig. 10, with others obtained from the network of recording gages. Each pair of patterns in Fig. 10 represents a time period of approximately 1 min.

There is considerable similarity between the two rainfall patterns and between their paths of movement across the area of the rain gage network. Variations between two in a pair may be partially attributed to the fact that radar "views" precipitation particles at an altitude above the ground. As the rain falls earthward. it drifts with the air currents and, consequently, does not strike the ground immediately below the point where it was recorded by the radar. In addition, the rainfall pattern from the gage network has to be prepared from point rainfall measurements that are 1-2 miles apart, whereas the radar observes precipitation over an entire area. Attenuation (loss of signal strength from scattering and absorption by intervening raindrops) often causes a loss of radar-indicated contour areas, especially on the far side of a storm (P).

In the Illinois Water Survey research program on the utility of radar in measuring rainfall, it was desired to determine the accumulation of rainfall as well as its distribution pattern. The rainfall intensity indicated for each echo contour shown in Fig. 10 can be computed from an expression like Eq 3 (page 847). The amount of rainfall represented by each isoecho contour map can be obtained by multiplying the area between contours by the proper rainfall rate and summing these products. By repeating this process for all minutes during the storm, the total rainfall volume can be obtained. Dividing the latter figure by the network area gives the network mean depth.

Empirical Equation

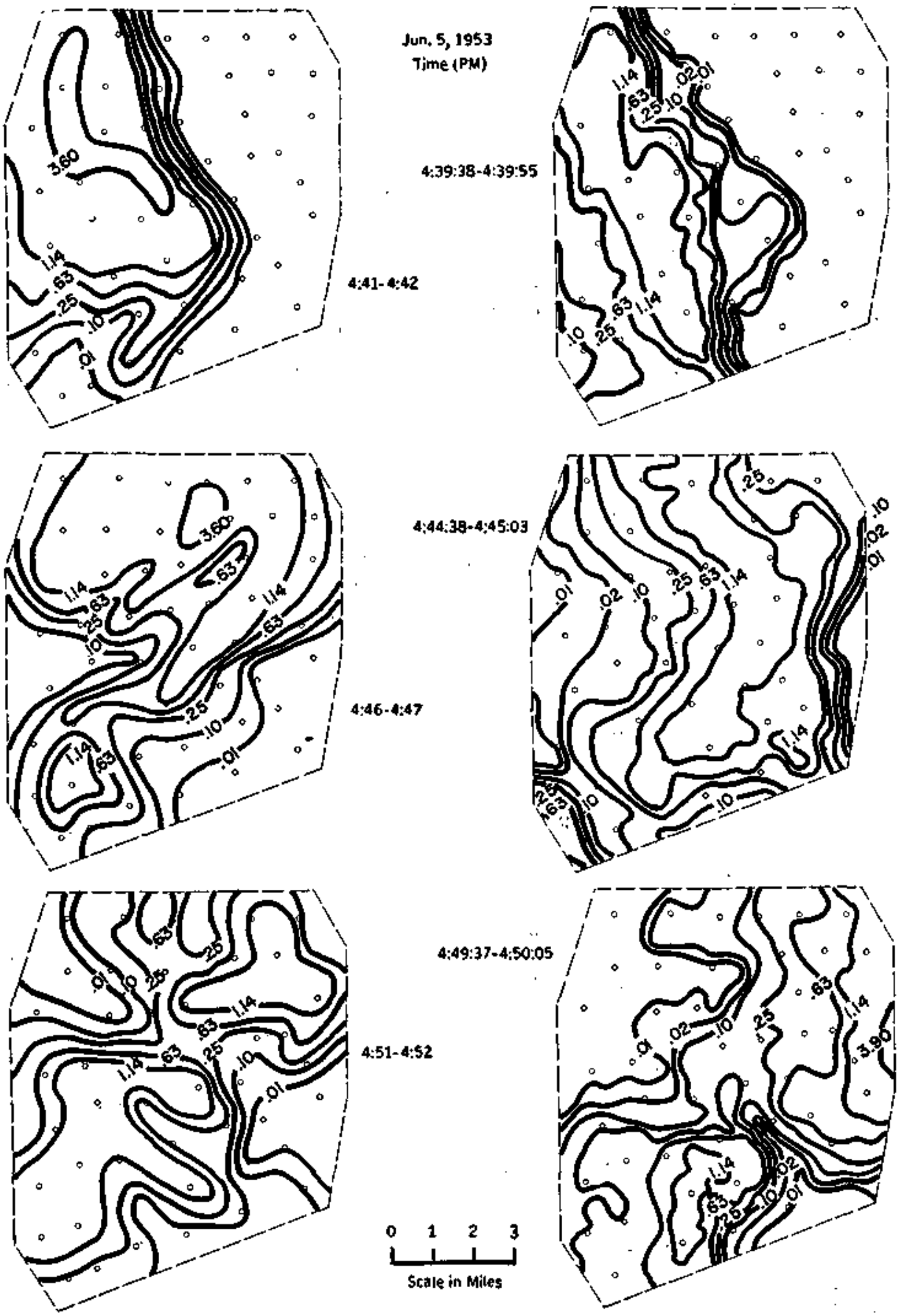
The Illinois radar data indicated that previously published theoretical radar rainfall equations like Eq 3 gave rainfall intensities that were extremely small in comparison with those obtained from the rain gage network. Accordingly, it was decided to develop an empirical radar rainfall equation from radar and gage data collected during the thunderstorm season of 1953. The resulting equation was:

$$\log \frac{P_r R^2}{P_t} = 2.00 \log I - 11.641 \quad (4)$$

in which P_r is the power received (w), P_t is the power transmitted (w), R is the range (nautical miles) from the radar set to the reflecting raindrops, and I is the rainfall intensity (iph).

Areal mean rainfall depths for thirteen storm, periods in 1953 were computed with both Eq 3 and Eq 4 (Table 1). Rain gage data indicated that the Goose Creek watershed accumulated an average depth of 3.96 in. during the thirteen storms. An estimate of 2.34 in. was obtained when the empirical equation (Eq 4) was used, while the theoretical equation (Eq 3) gave an estimate of 0.80 in. for the same storm periods. Table 1 shows that, in general, the empirical equation gave much larger and more accurate rainfall depths than Eq 3. .

The preceding analytic process is very laborious and time consuming. In order to obtain a prompt estimate of areal mean rainfall, an area-rainfall integrator has been designed and built by State Water Survey electronic engineers. This device (shown at right in Fig. 7) electronically integrates the power returned from reflecting **rain-**



Isohyetal Pattern isoecho Pattern

Fig. 10. Gage and Radar Maps of Rainfall (iph)

drops as the storm moves over an area. A cumulative record of the areal mean rainfall is automatically printed on a tape at 1-min intervals during a storm. At the end of the storm, an estimate of the accumulated areal mean rainfall is available as promptly as the point rainfall amount from a recording rain gage. The integrator is presently undergoing testing and minor modifications.

TABLE 1

Radar and Rain Gage Mean Rainfall Comparisons

Date (1953)	Gage Depth—*in.*			Radar Avg Depth—*in.*		Radar Minus Gage Value†	Radar Accuracy Equivalent Gages‡
	Min.	Avg	Max.	Eq 4	Eq 3		
4/9	0.00	0.05	0.23	0.18	0.06	+0.13	<1
4/24	0.09	0.12	0.48	0.25	0.06	+0.13	<1
5/16	0.03	0.21	0.48	0.26	0.06	+0.05	1
6/5*	0.13	0.35	0.55	0.32	0.12	−0.03	5–6
6/8*	0.31	0.60	0.94	0.48	0.22	−0.12	≪1
6/25*	0.01	0.71	1.25	0.25	0.10	−0.46	≪1
7/2	0.03	0.44	1.64	0.06	0.01	−0.38	≪1
7/5	0.64	0.82	1.03	0.13	0.04	−0.69	≪1
7/17*	0.01	0.15	0.37	0.15	0.05	0.00	50
8/3*	0.00	0.03	0.23	0.03	0.01	0.00	50
8/7	0.21	0.37	1.55	0.15	0.05	−0.22	≪1
8/8*	0.00	0.09	0.59	0.05	0.01	−0.04	1
9/18	0.00	0.02	0.07	0.03	0.01	+0.01	1–2
Total		3.96		2.34	0.80		

* Storms from which Eq 4 was obtained.

† Difference between radar depth computed from Eq 4 and average gage depth.

‡ Number of gages per 96 sq miles whicli would be expected to give a result as accurate as that obtained with radar using Eq 4.

Radar Accuracy

In experimental estimation of rainfall over a 96-sq mile watershed with radar instrumentation, it is necessary to adopt some standard as a basis for judging the reliability of the method. The rainfall sampling variance study, described previously, can. be used for this purpose. The deviation (shown in the next-to-last column of Table 1) of the radar rainfall depth from the average on the Goose Creek gage network was compared with the sampling error (Fig. 5) for various gage densities. The results of this comparison are shown in the last column of Table 1. It was found that, in five storms, the deviation between the radar and the rain gage mean depth was considerably larger than the sampling error expected with one gage per 96 sq miles; in two storms, the deviation was slightly larger than that expected with one gage; in four storms, the deviation compared favorably with the error expected with one or two gages; and in two storms, there was no deviation from the 50-gage network mean.

The very low radar estimates on Jul. 2 and 5 can be at least partially attributed to attenuation of the transmitted and received signals by the rainfall between the network area and the radar. With 3-cm radar, attenuation occurs during heavy rainfall, although, if longer wavelengths are used, the rainfall does not seriously weaken the signal. On Jul. 5 there was rain at the radar station itself during the period of data collection. Except for that instance, all radar rainfall depths in Table 1 were between the lowest and highest gage readings on the network. When the proper radar wavelength for quantitative precipitation measurements is employed, the attenuation factor may be negligible.

Conclusion

With present accuracy, radar rainfall measurements can supplement thunderstorm rainfall sampling by the existing Illinois climatological rain gage network of approximately one gage for every 225 sq miles. The average area of a thunderstorm is approximately 8 sq miles, which corresponds to a diameter of about 3 miles for a circular cell. Therefore, it is possible for thunderstorms of this size to pass between gages of the Illinois network. Radar scans an entire area and is not subject to such measurement errors. Radar both locates and measures rainfall, whereas a rain gage cannot sample rainfall unless the rainstorm passes over it.

The results of the Illinois Water Survey 3-cm radar study are encouraging enough to indicate that further research on the quantitative measurement of rainfall with radar instrumentation should be carried out with up-to-date radar equipment using longer wavelengths, which are theoretically not as subject to raindrop attenuation.

Acknowledgment

The valuable assistance of M. Spock and L. Bivans, who were associated with the radar study project as meteorologists, is gratefully acknowledged. R. Cipelle performed many of the computations. Credit is due various other staff members who either operated and calibrated the radar equipment or collected the rain gage data.

Quantitative measurement of rainfall by means of radar was first suggested by Byers *(10)* in 1948.

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